LEFT HANDED MATERIALS IN MAGNETIC NANOCOMPOSITES

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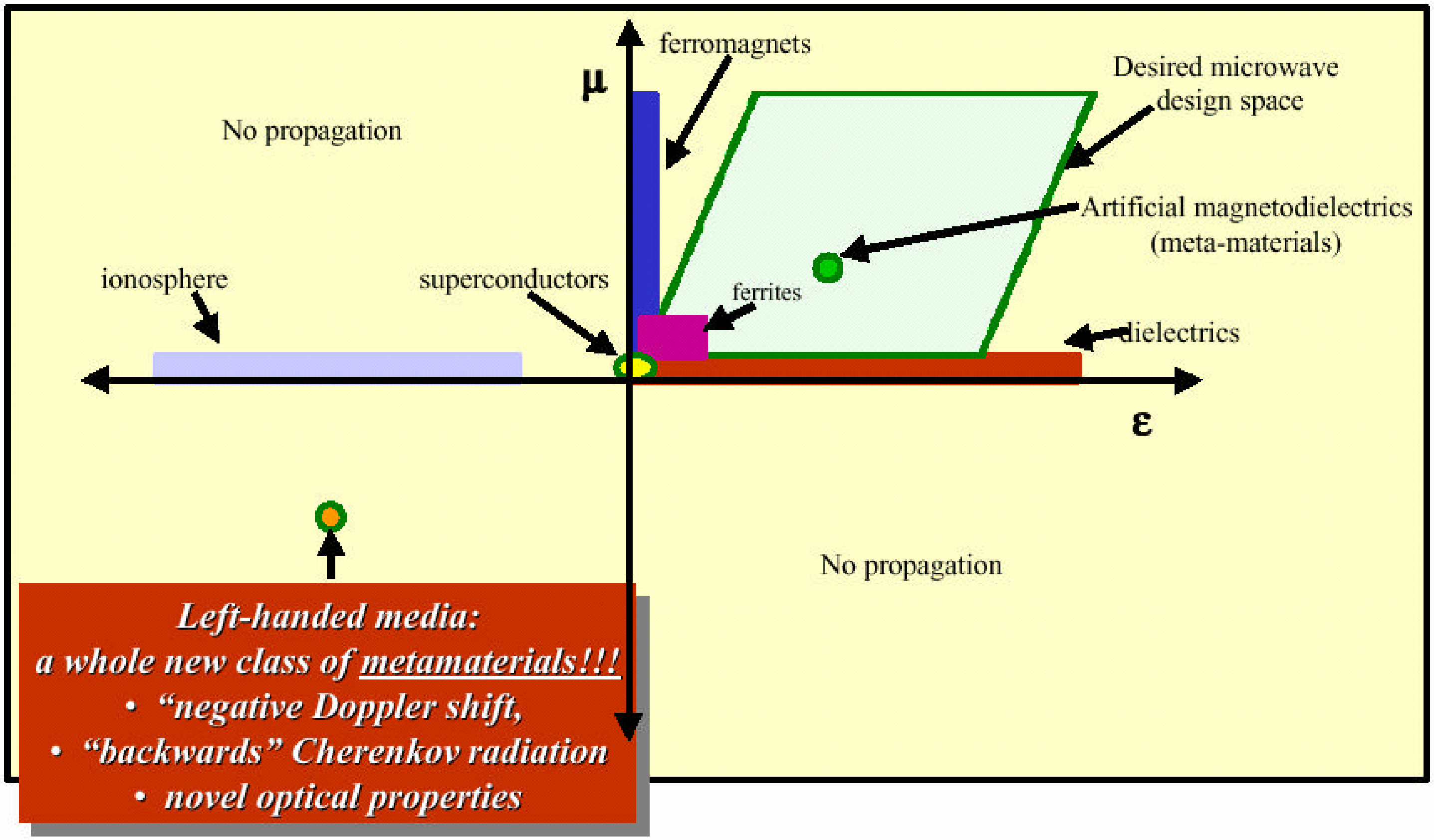
Propagation Properties of Different Materials

Speed of light: $C = \frac{1}{\sqrt{em}}$

ε: dielectric permittivity
μ: magnetic permeability



LHM: Energy Propagation Opposite to Wave Propagation

Convention Materials(RHM):

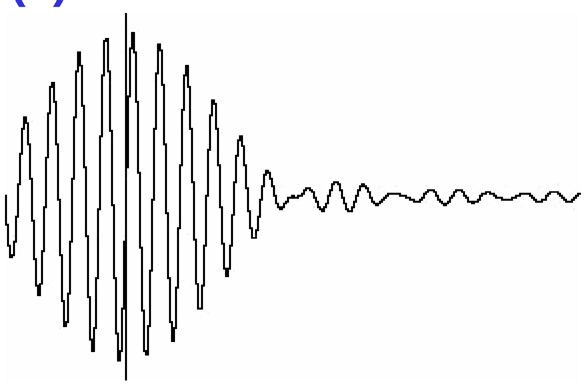
$$\vec{E}(\vec{r},t) = \vec{E}_0 e^{ikz-bz-iwt}$$

$$\vec{H}(\vec{r},t) = \vec{H}_0 e^{ikz-bz-iwt}$$

$$\vec{E} \times \vec{H} \Rightarrow \vec{k} = w\sqrt{e(m \pm m')}$$

$$\vec{E} \times \vec{H} \Rightarrow \vec{S}$$

Wave propagates(phase velocity) in the same direction of energy flow(k)



Left-Handed Materials(LHM):

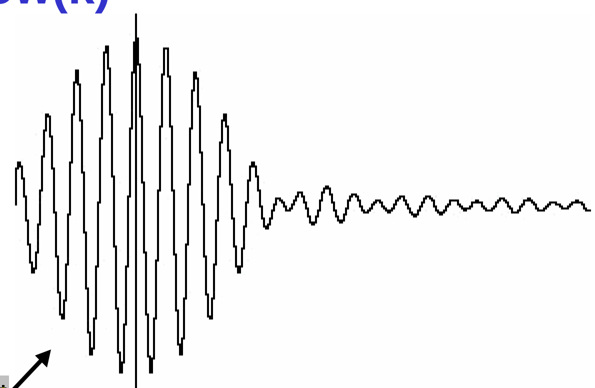
$$\vec{E}(\vec{r},t) = \vec{E}_0 e^{-ikz-bz-iwt}$$

$$\vec{H}(\vec{r},t) = \vec{H}_0 e^{-ikz-bz-iwt}$$

$$\vec{E} \times \vec{H} \Rightarrow -\vec{k} = w\sqrt{e(m \pm m')}$$

$$\vec{E} \times \vec{H} \Rightarrow \vec{S}$$

Wave propagates(phase velocity) in the opposite direction of energy flow(k)



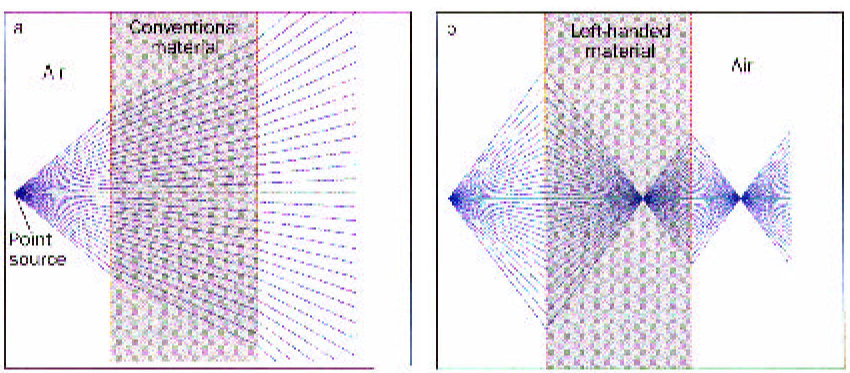
Key Ideas of LHM

- **Negative dielectric constant**
- **Negative magnetic permeability**
- **Light propagation may not be damped**

Key feature: The direction of energy flow is opposite to the direction of the wave vector!

Unusual Physical Properties

1. Reversed Doppler effect – microwave radiation or light shift to lower frequencies as a source approaches and to higher frequencies as it recedes.
2. Reversed Cerenkov effect – light emitted in the backward direction (forward direction in a right-handed materials) when a charged particle passes through a medium.
3. Reversed Snell's law – light that enters a LHM from a normal material will undergo reflection, but opposite to that usually observed.
4. Unusual lens:



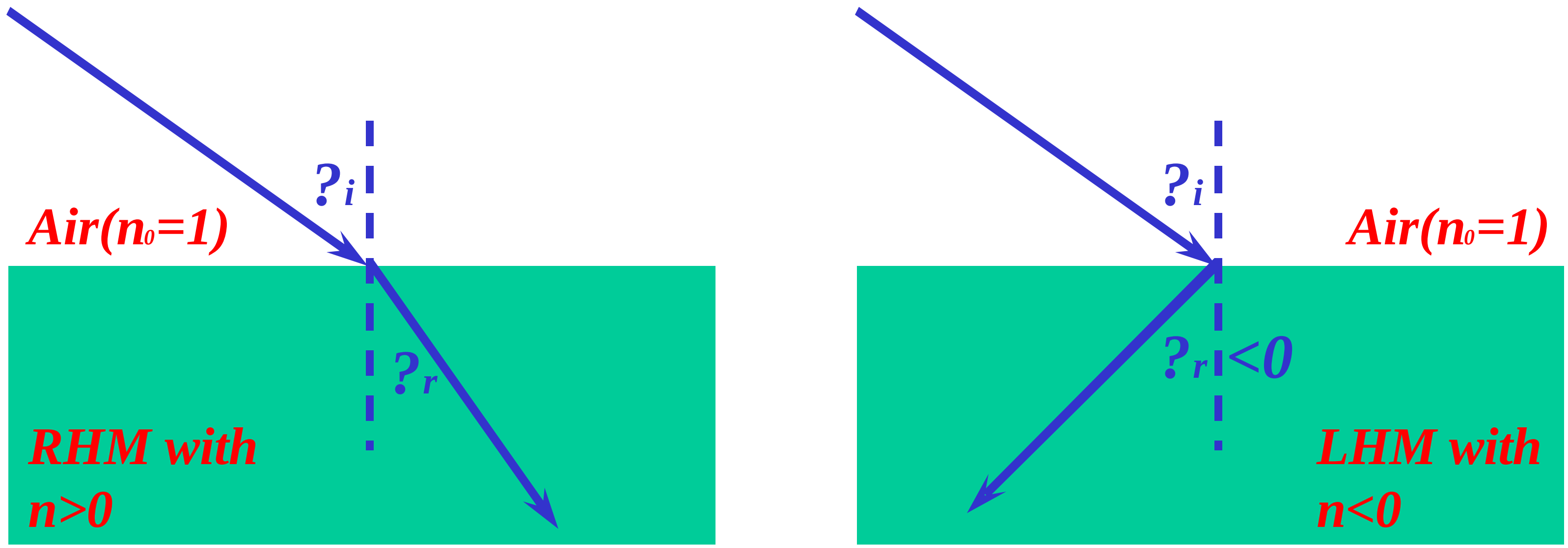
Radiation emanating from a point source in air that is incident on a conventional right-handed material (a) diverges, but on a left-handed material (b), it converges.

Negative Index of Refraction

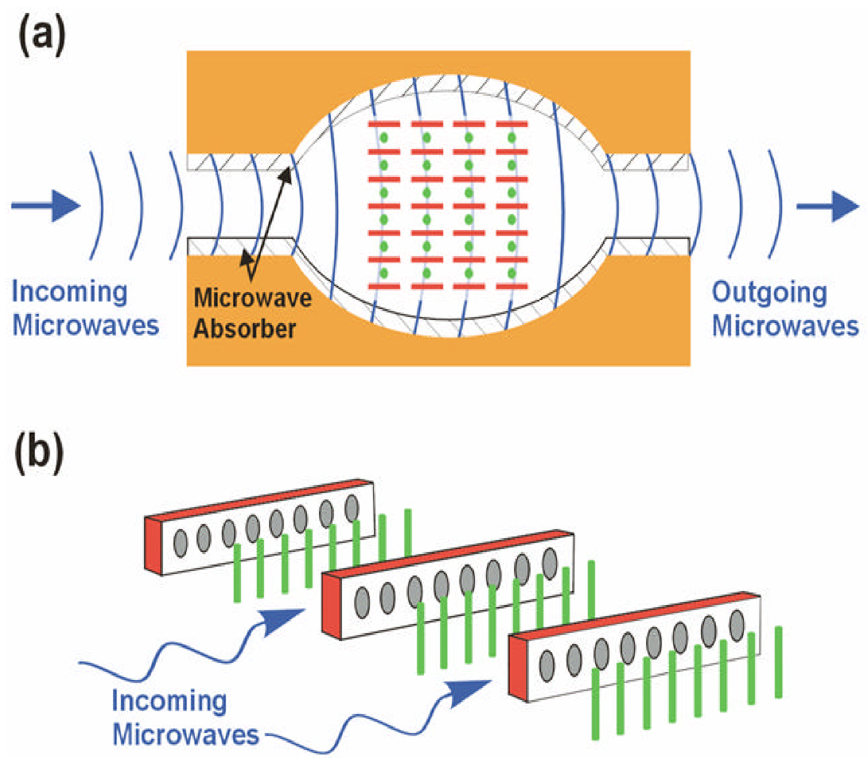
According to Snell's Law:

$$\sin q_r = \frac{n_0 \sin q_i}{n}$$

Reversed refraction can be observed at interface between RHM and LHM.



Current Left-Handed Materials



Since these materials are made by microstructure, they are very difficult to be used

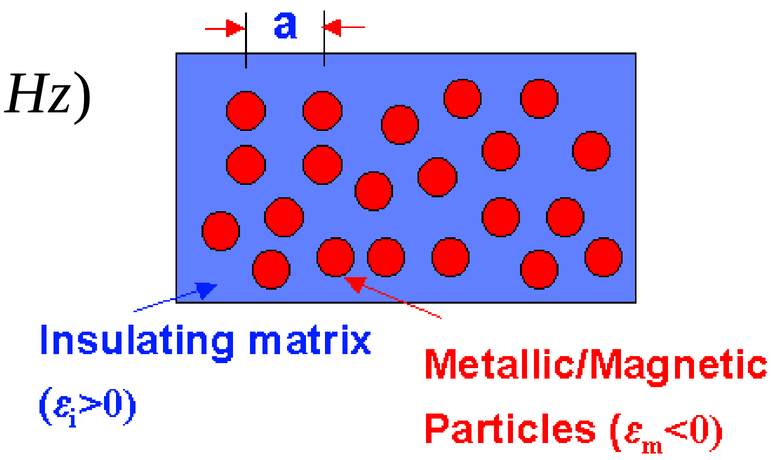
Negative e and m in Composite Materials

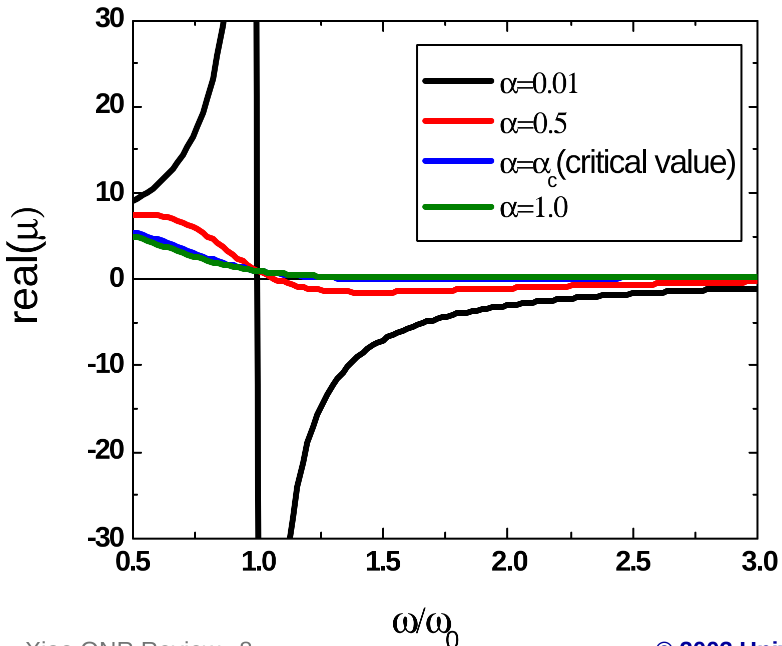
metals : $e_m < 0$ at $w < w_{plasma}$ $(UV, 10^{15}\,Hz)$

dielectric s : $e_i > 0$

Effect medium theory: $\lambda > a$

$$e_{eff} = f e_m + (1 - f) e_i$$





- **Negative magnetic permeability can be obtained by ferromagnetic resonance (for RCP Waves);**
- **Small Particles and polymer matrix are used to get small damping.**

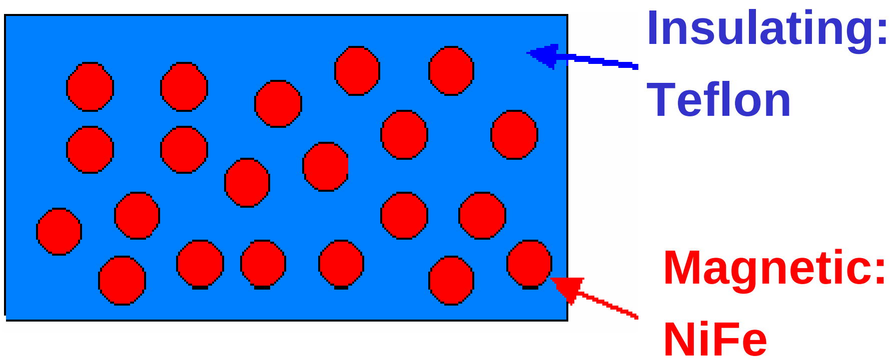
Effective Medium Approximation:

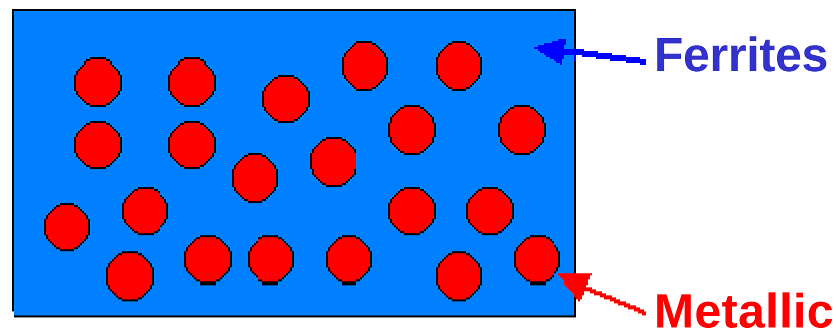
- Medium is LHM for right circularly polarized waves (RCP) propagating along the direction of the magnetization. Medium is RHM for LCP waves. mLHM is anisotropic and chiral!
- Metal concentration below the conducting percolation threshold but above the magnetic percolation threshold.
- The direction of energy flow is opposite to the wave vector.
- The damping turns out to be small, Im(keff)<<Re(keff)!

Chui *et. al.,* Phys. Rev. B65, 144407, 2002; PRB66, 085108-1, 2002.

Magnetic Composite Fabrication

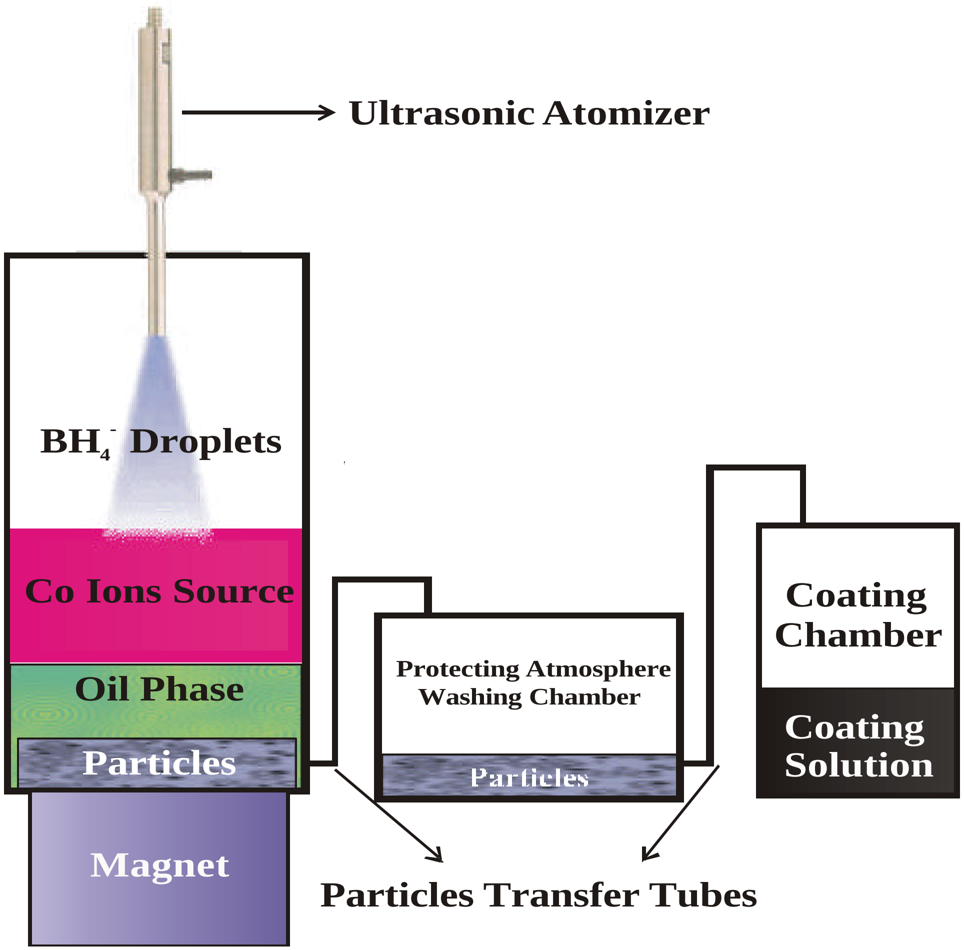
- Magnetic composites (films, and bulk materials)





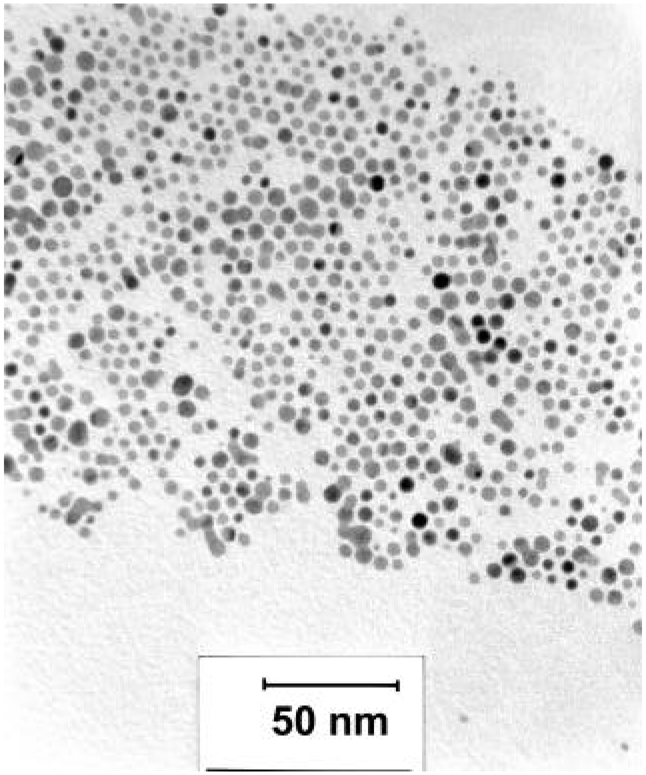
- Thin Films: Vapor deposition (magnetron Sputtering)
- Bulk Materials: Ball milling, chemical synthesis, and microcompounder
- FeNi: Low loss, resonant frequency can be tuned with composition, and large negative permeability.
- Teflon: Low loss and low dielectric constants

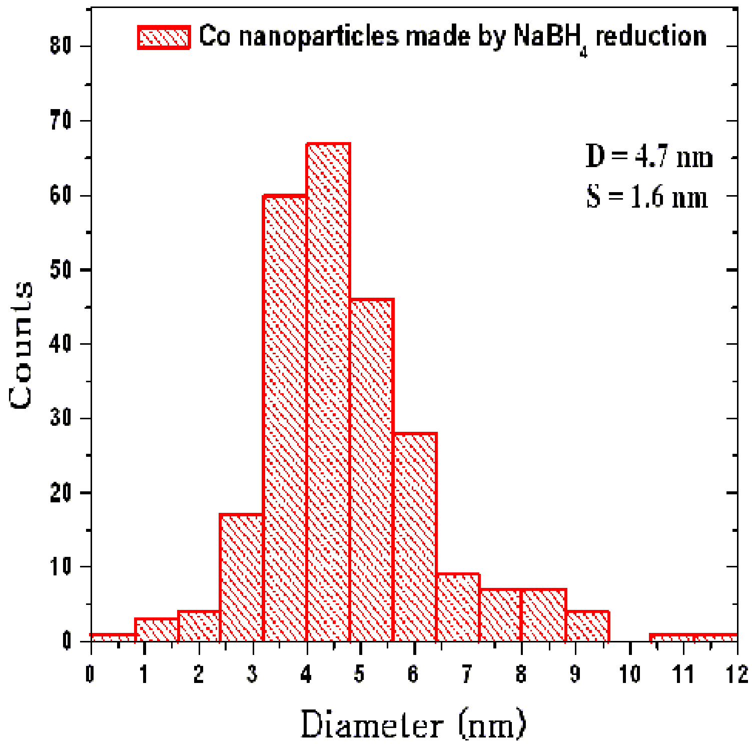
Mass Production of Magnetic Uniform Nanoparticles



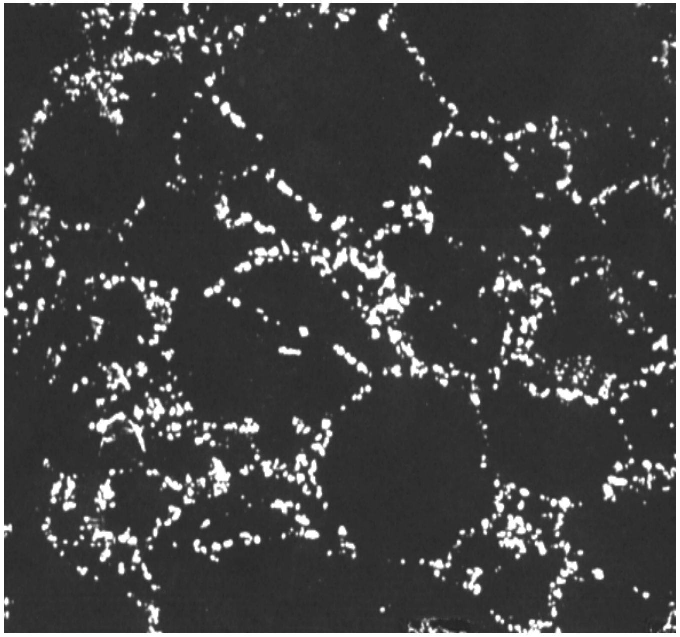
- **Modified chemical reduction method: mass production.**
- **Controlled nucleation and growth: uniform particle sizes**
- **Controlled environment: minimum oxidation and impurity phase.**

Example: Co Nanoparticles

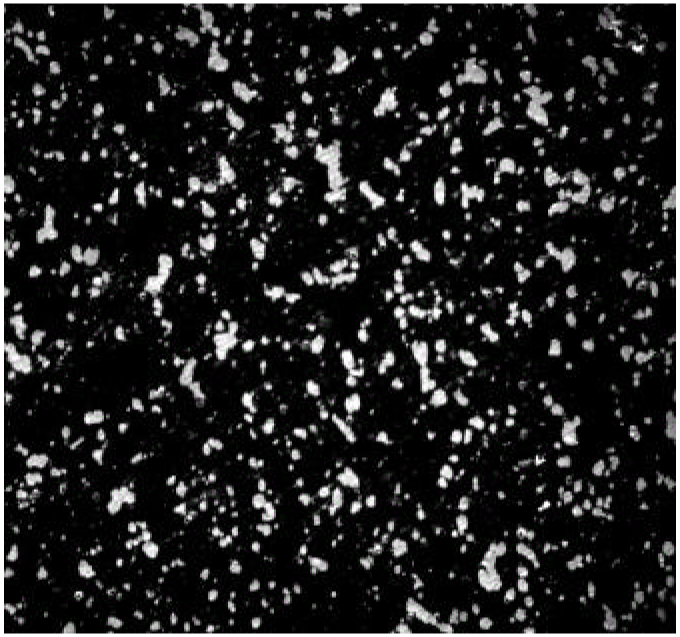




Monodispersed Magnetic Composites

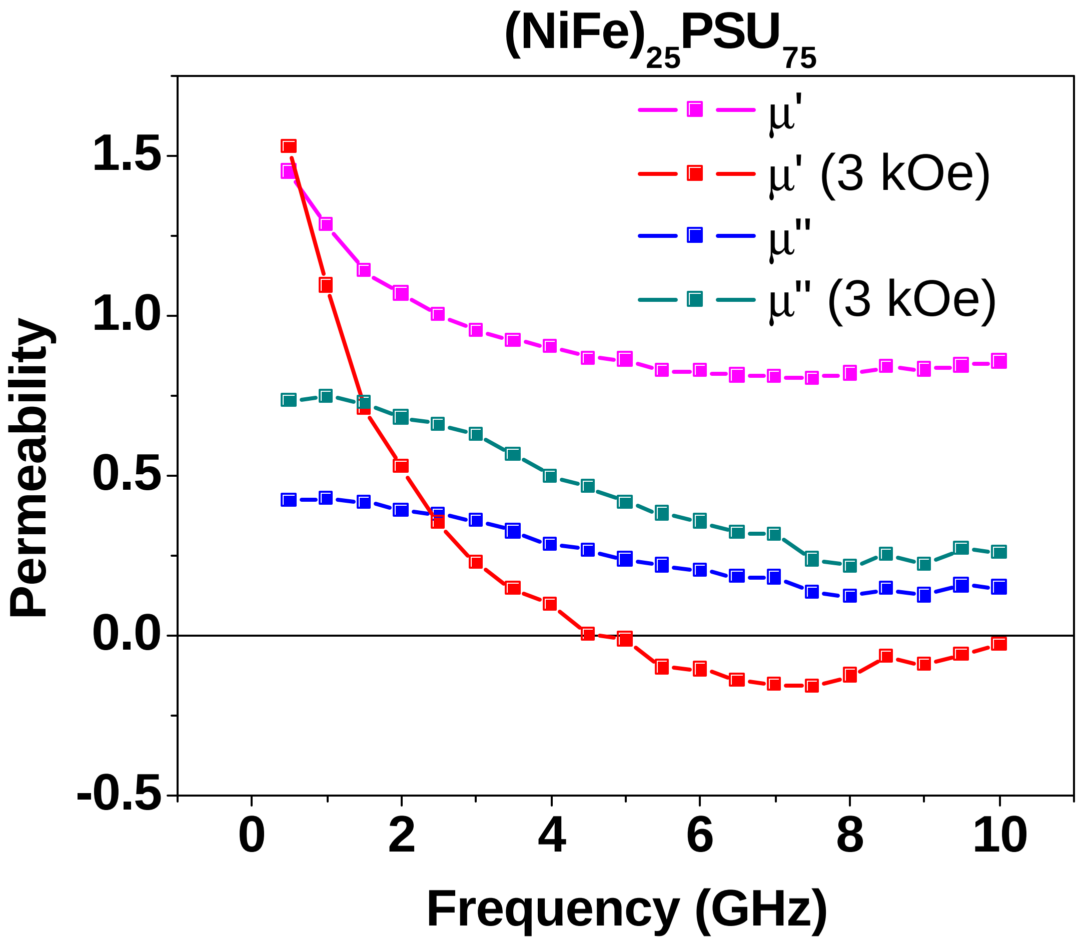


Dry powder mixing
and
Hot press



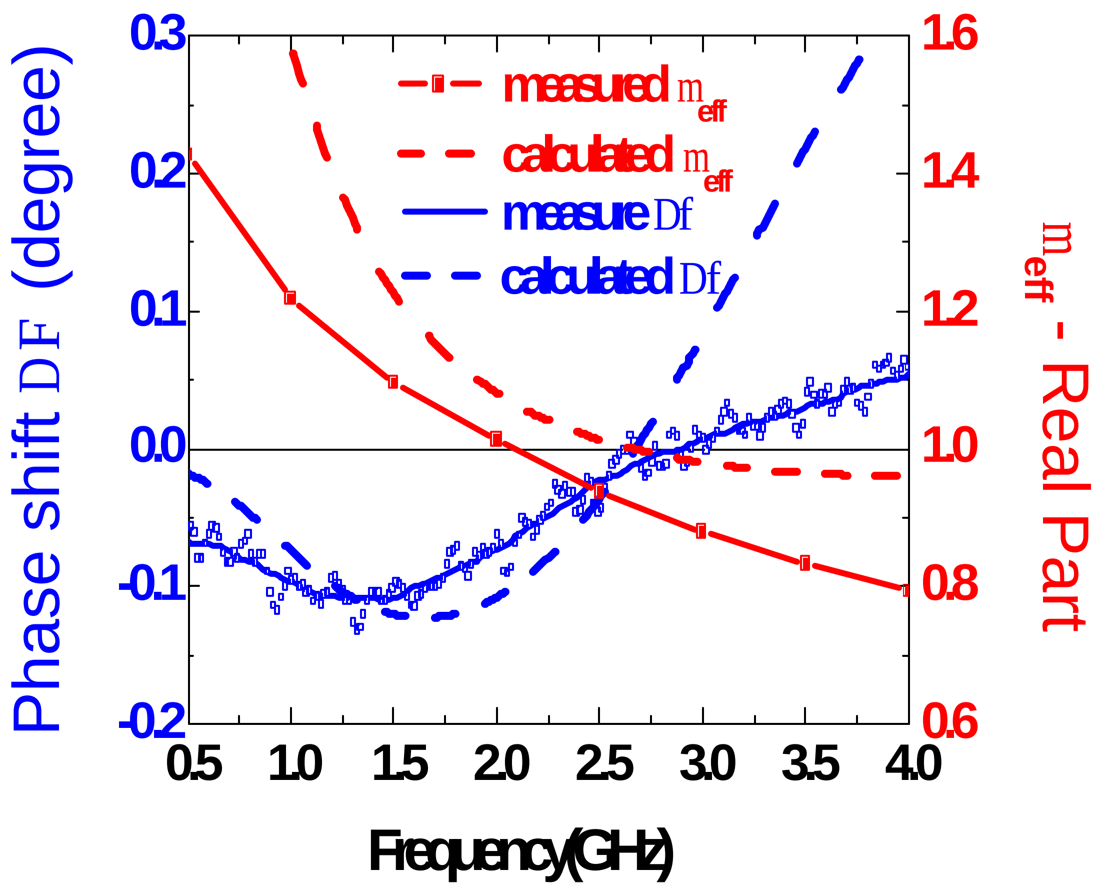
High Temperature
shear mixing
and
Hot press

Experiment: Negative Permeability

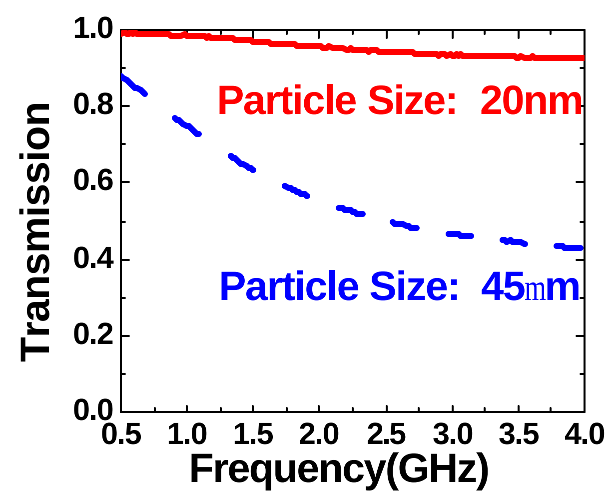


m < 0 can be achieved in magnetic composite. The sign can be tuned with an external magnetic field.

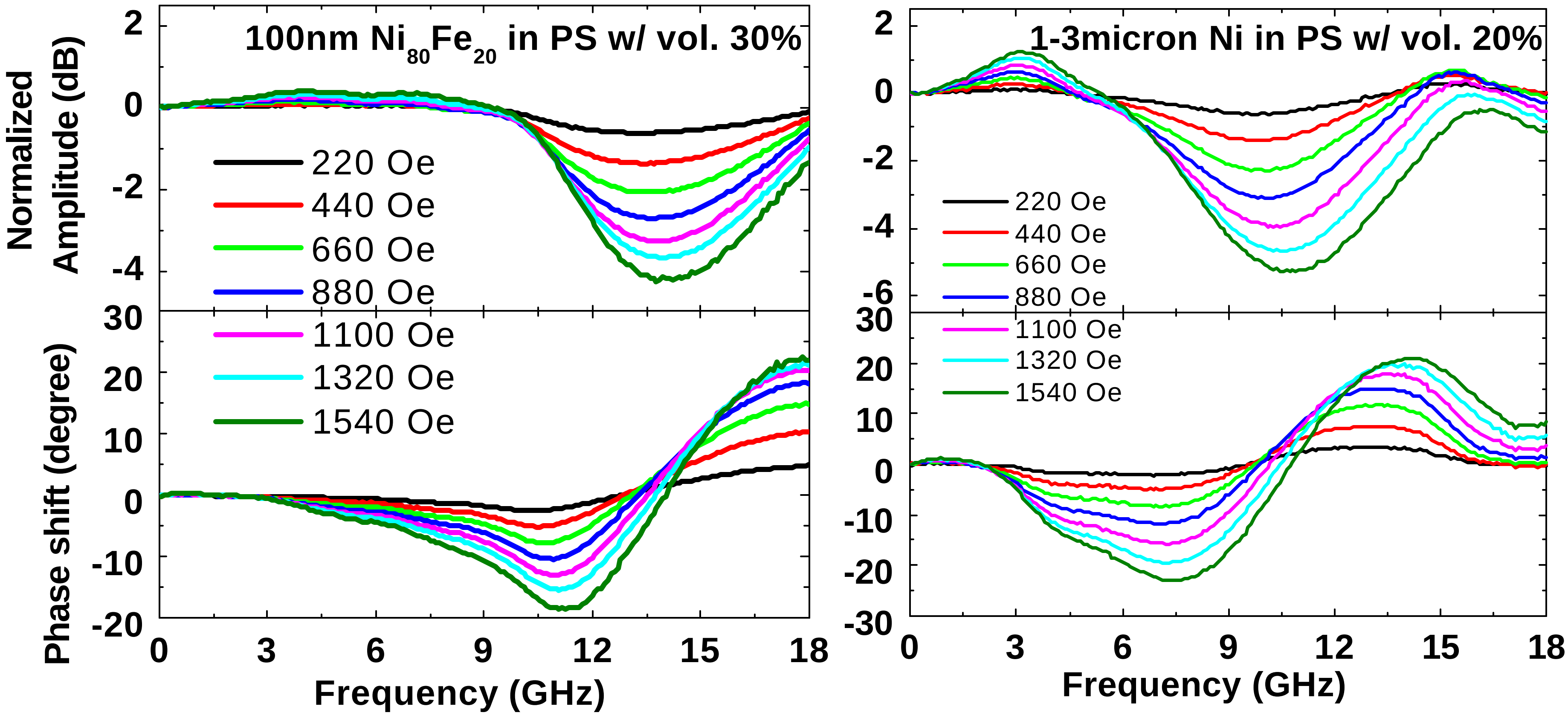
Abnormal Transmission Phase Shift: a Possible Sign for mLHM



- Abnormal phase shift at $\mu_{eff} < 1$ ($\chi < 0$), due to reverse of k direction
- Good theoretical fittings! (dash lines)
- Low loss with small particles

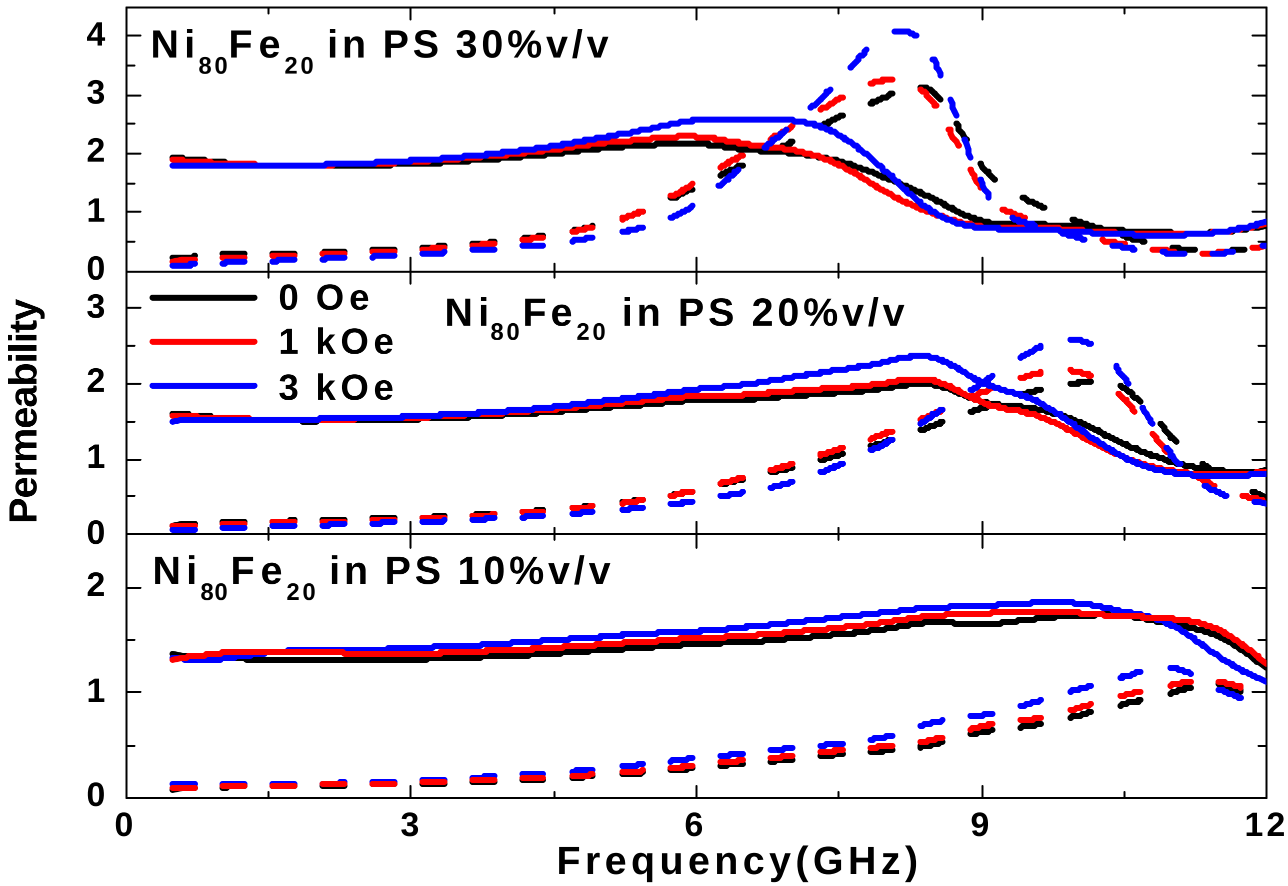


Transmission - Field Dependence



Phase shift can be enhanced by the external magnetic field

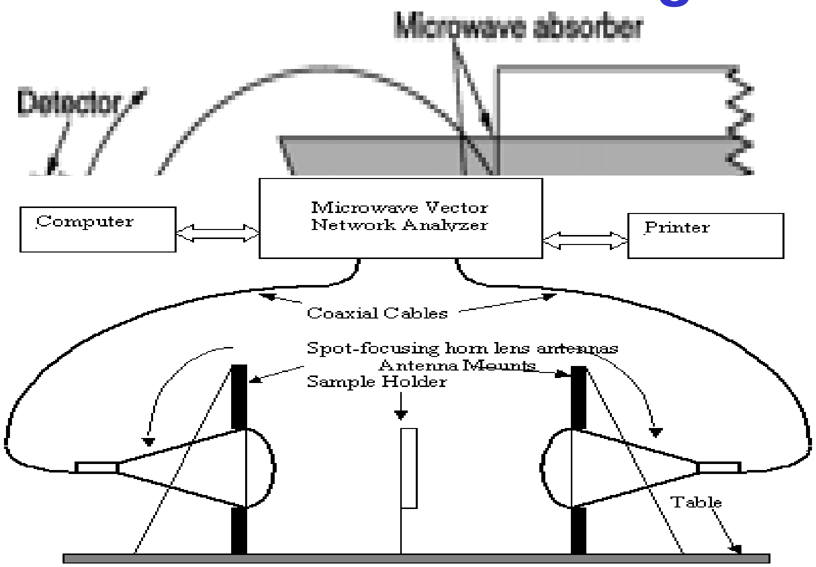
Transmission - Composition Dependence

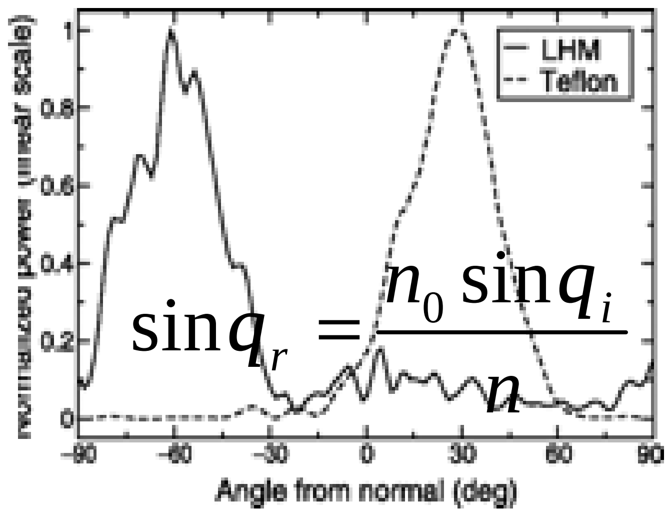


Permeability spectrum can also tuned by the composition.

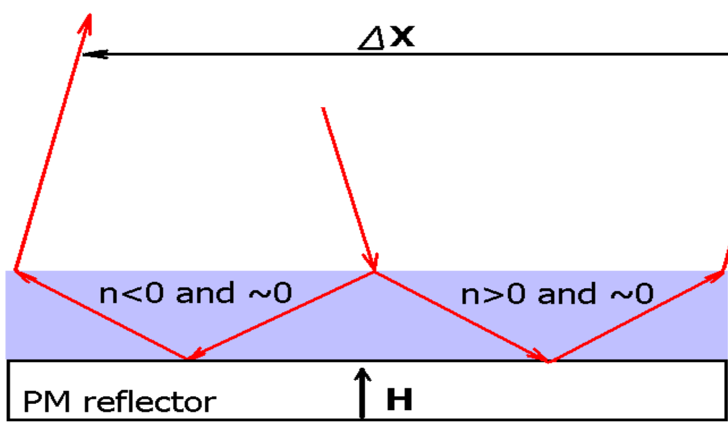
Direct Prove of Negative Refraction Index in Open Space

Negative refraction index can be proved by the fact the refracted wave will change direction at around n~0

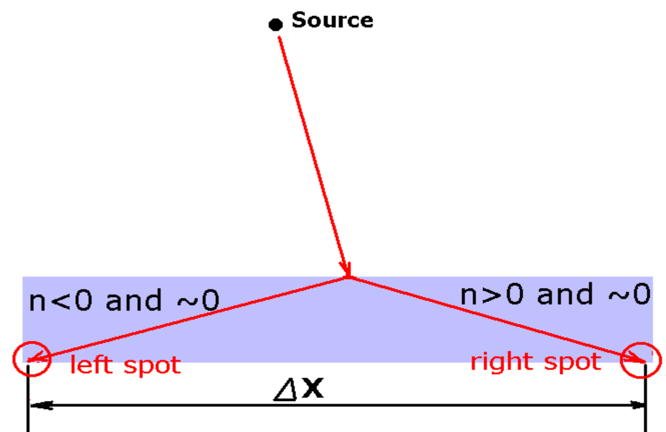




$$\sin\theta_r = \frac{n_0 \sin\theta_i}{n}$$



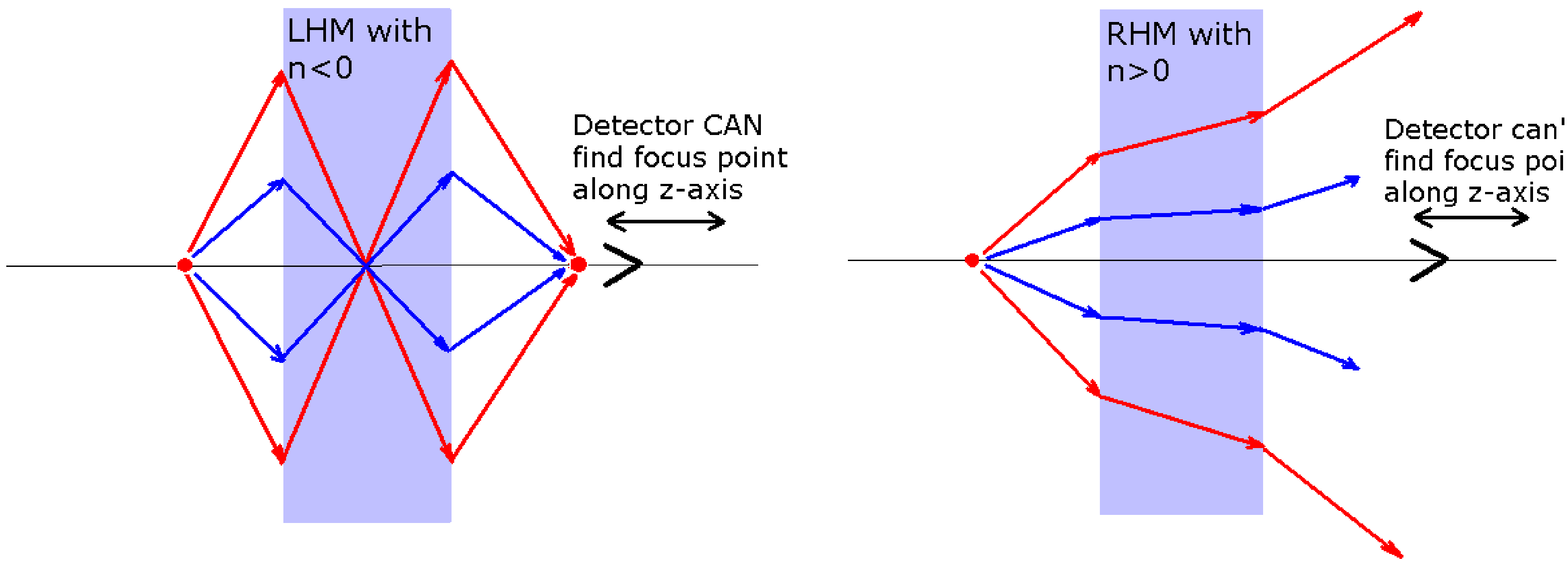
(b)



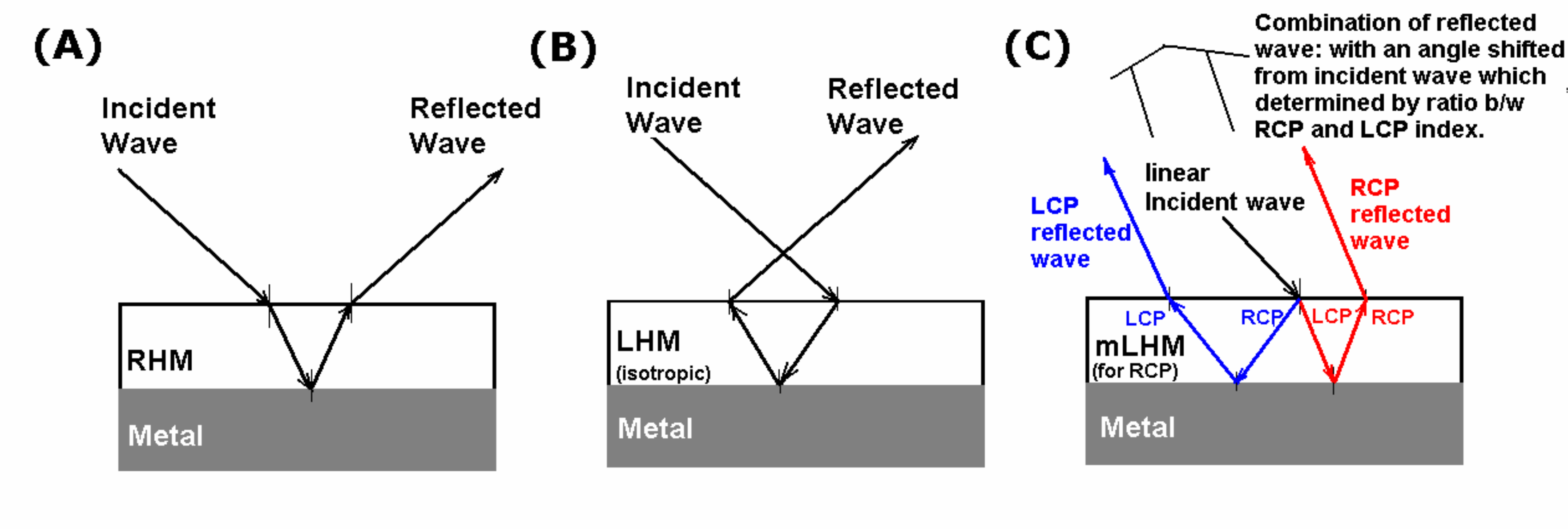
(a)

Direct Prove of Negative Index in Open Space

**Another open space experimental setup:
Find focus point on the other side of a mLHM slab.**



Special Properties of Anisotropic and Chiral mLHM



(A) RHM:

Standard reflection behaviors

(B) Isotropic LHM (rings and rods) :

Same reflection behaviors as RHM

(C) mLHM:

LHM for RCP & RHM for LCP along the magnetization direction. abnormal reflection is obtained.

Conclusion and Future Work

- Magnetic nanocomposites are potential LHM: mLHM.
- mLHM is different from current isotropic LHM: mLHM is anisotropic and chiral.
- mLHM can be achieved in bulk quantities and have special applications.
- Transmission spectra depends on the composition and external magnetic field.
- Loss can be minimized using small magnetic nanoparticles
- Future work: demonstration of the negative of index in mLHM